Geochemistry of the Early Solar Nebula

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Harold Urey was responsible in the 1950s for introducing chemistry into the study of the solar system, following millennia of work on the dynamical aspects. The behavior of the chemical elements during nebular processes depends both on relative volatility and their entry into metal, sulfide or silicate phases. In the latter case, both ionic radius and valency control element distribution, so that large cations such as potassium and other volatile elements are not expected to be present in forsterite or enstatite grains. The inner nebula was depleted not only in the gaseous and icy components of the original nebula but also in those elements that are volatile below about 1100K. This depletion is observed in most meteorites, except for the Type 1 carbonaceous chondrites (CI) that match the solar photospheric abundances for the non-gaseous elements. The depletion is most readily measured by the K(volatile)/U (refractory) ratio (although K and U are unrelated chemically, both elements finish up in residual liquids during crystallization of silicate melts and so approximate the bulk planetary ratio in planetary surface samples). Low K/U ratios are also observed in the bulk compositions of Venus, Earth and Mars so that the depletion of volatile elements, relative to the primordial nebular abundances (CI), is a widespread feature within 3–4 AU of the Sun. Thus the early inner nebula was both bone-dry (the primary mineralogy of meteorites is anhydrous) and depleted in volatile elements including the biologically useful elements such as C, N, P and K. Potassium isotope ratios are invariable in the inner nebula and show no effects attributable to Raleigh fractionation that might be expected during condensation from or evaporation in a hot nebula. While Mg and Fe will occur mostly in interstellar grains in refractory olivine and pyroxenes, K and other volatile elements are expected to occur mostly in other phases (glass, feldspar?). Processes responsible for volatile loss may include early solar activity driving out the gaseous and volatile components to a “snowline” around 5 AU and selective evaporation of grains of differing mineralogy drifting into higher temperature zones in the nebula near the early Sun. Volatile element depletion is observed in the components (e.g., chondrules) of chondritic meteorites and so occurs before chondrule formation, close to T_0 (4566 ± 5 m.y.). The REE patterns in refractory inclusions (CAIs) record extreme temperatures (>2000K) probably due to repeated evaporation and condensation episodes near the Sun (X-wind model) but chondrules were the products of flash melting (~2000K) in a cool nebula. The timing of these events places the formation of the chondrules about 2 m.y. after the CAIs, followed shortly after by the accretion of chondrules, CAIs and matrix into the chondritic meteorites. Formation of planetesimals and asteroidal-sized bodies occurred rapidly with Vesta (450 km diameter) accreting, differentiating and producing basaltic lavas within a few million years of T_0, apparently well within a putative 10 m.y. age for the gaseous nebula. This might indicate decoupling of the gaseous and rocky components during nebular evolution, planetesimals being presently undetectable in disks. Stochastic accretion of the inner planets from planetesimals (probably already differentiated into metallic cores and silicate mantles) takes from 10–100 m.y. in current models. As the Earth does not have the CI value for major elements such as Al/Si or Mg/Si, this indicates that additional element fractionation has occurred both between metals and silicates and within the silicate fraction during planetary accretion from planetesimals. When nature got around to building two similar rocky planets, it produced the Earth and Venus that recall Dr. Jekyll and Mr. Hyde. These twins, unlike Mars and Mercury, are close in mass, density, bulk composition and in the abundances of the heat producing elements (K, U and Th), but the subsequent geological evolution of these “twin” planets has been wildly different. This reinforces the point that similarity is not identity and emphasizes the difficulties in characterizing terrestrial planets.